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Technologies for Autonomous Sailing: Wings and Wind Sensors

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***Abstract*—The current generation of sailing robots require a small number of essential components in order to function successfully. These include some kind of sail and a device for detecting the direction of the wind, in order to ensure that the angle of attack of the sail is suitable for the course to be sailed. These two devices present some of the most difficult engineering and control system challenges in building sailing robots. This paper summarises a number of experimental designs and approaches to the construction of these components. In particular a number of wingsail construction and control techniques are presented as well as designs for mechanical and ultrasonic wind direction sensors. All of the devices presented have been built and tested by the authors. Commentary on the performance and interaction of the devices is also presented.**

I. Introduction

Sailing robots require some kind of sail to propel them through the water, to date two key designs have emerged wing sails and traditional fabric sails controlled through sheets (ropes). Wing sails offer far fewer points of failure but suffer from poor downwind performance and currently lack a reliable method of reefing. In order to set the sail position correctly the boat's control system must know the current direction of the wind and therefore some kind of wind direction (and possibly wind speed) sensor is required. There are two main approaches to sensing wind direction, mechanical sensors using a wind vane and ultrasonic sensors which sense the movement of air between an ultrasonic transmitter and receiver.

II. Sails and wingsails

Sailing vessels have evolved over many thousands of years through a huge range of shapes, sizes and technologies. All of these vessels until the last few years have been sailed by humans with varying amounts of mechanical assistance ranging from simple rope purchases, through manually operated and steam-powered capstans to modern electric and hydraulic winches on large modern yachts. The role of conservatism and tradition in this evolution should not be underestimated, and is often reinforced in the current era by the nature of racing classes and regulations. Despite this inherent conservatism a wide range of innovative designs have been experimented with over the years and some of these designs have shown great promise. Modern junk rigs, wing sails and kites are good examples of these technologies and clearly demonstrate that there is nothing particularly special about the conventional flexible fabric sail.

Flexible fabric sails have a number of useful properties on manned vessels under conventional conditions:

- They can be conveniently lowered and stowed when in harbour.
- They can be reduced in area relatively easily by either conventional "reefing" or by exchanging sails.
- They can be relatively easily repaired and modified.
- Their shape and camber can be altered by tensioning and releasing control lines.

They also have a number of problems:

- They are prone to wearing and tearing when incorrectly set.
- They lose their shape when not kept with a sufficient angle of attack leading to "luffing" which reduces sailing efficiency when close-hauled and eventually leads to "flogging" and potentially catastrophic failure.
- They require rigid structural spars and (often) wire rigging to maintain their shape: these introduce aerodynamic drag weight high above the waterline.
- They tend to twist which leads to different angles of attack at different points on the sail, this reduces sailing efficiency.

From the perspective of designing a sailing robot there are some very good reasons for considering the use of alternative sail types and in particular we have experimented with wingsails for various reasons[1], [2]:

- They can easily be designed such that they do not suffer from problems with chafing.
- They will not "flog" even when the control system fails to maintain the correct angle of attack.
- They maintain efficiency even when sailing very close to the wind.
- They do not necessarily require any additional structural elements to support them.

There are however significant disadvantages which should not be ignored. These include the fact that it is extremely difficult to design a wingsail which can be reefed reliably and that it is relatively difficult to construct strong, lightweight rotatable wingsails at reasonable cost. We however maintain that the potential gains in reliability and efficiency outweigh these problems and we have successfully constructed and tested a number of sailing robots equipped with wingsails of various designs. We have also experimented with a number of actuator technologies appropriate for their control. We have focused on *designing* for longevity, low power consumption and simplicity and *constructing* for reliability and robustness. We do not aim for or claim that our systems are in any sense optimal in terms of sailing efficiency, but the later systems are sufficiently efficient, robust, controllable and low in power consumption to allow long term autonomy to be possible.

A. AROO's wingsail

AROO[3][4] (Autonomous Robot for Ocean Observation) was the first sailing robot constructed by Aberystwyth University during the autumn of 2004. It was decided that a wing sail was best suited due to its potential robustness. The wing was constructed from a folded sheet of scrap aluminium (which was originally part of a London Bus!) and was $125\,\mathrm{cm}$ tall and $18\,\mathrm{cm}$ long ($225\,\mathrm{cm}^2$ area). It was controlled by a DC electric motor with position detected by a potentiometer as shown in figure 2. A mechanical wind vane and potentiometer were placed on top of the sail to sense wind direction, as shown in figure 1. One unfortunate problem with this design was that the sail could be continually rotated and the cable linking the wind sensor to the rest of the boat could easily become tangled around the mast. Despite these problems the wing performed exceptionally well in winds up to 30 knots. The sail was if anything too large for the boat (a $1.5\,\mathrm{m}$ long racing monohull) and caused some stability problems and difficulties for the steering system. Given the inability to reef a wing sail this design would not have been appropriate for a sea going boat which is likely to encounter winds far in excess of 35 knots.

Fig. 1. AROO's Aluminium Wing sail with a rotary wind sensor on top.

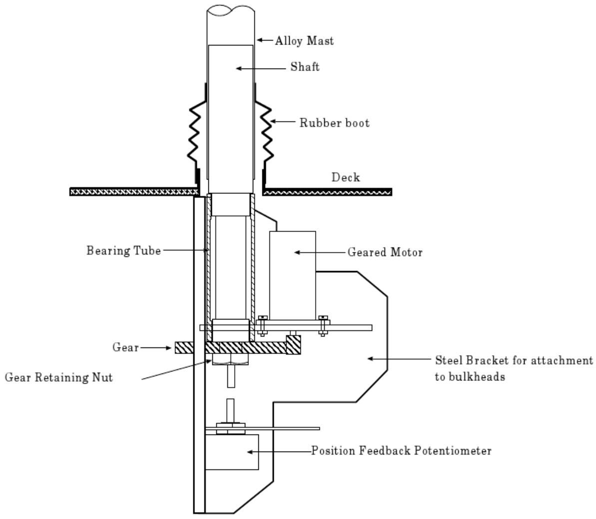

Fig. 2. AROO's sail drive mechanism.

B. ARC's schooner wingsails

In designing the second boat at Aberystwyth, ARC [5][4] (Autonomous Robotic sailing Craft) we opted for dual wing sails in a schooner configuration.This was intended to counter the instability which had been observed with AROOs sail. These were constructed of lightweight acrylic wrapped around several wooden blocks to retain shape, making them significantly lighter and easier to handle than AROOs sail. They were relatively easy to construct, needing only to cut the wood blocks, fold the acrylic and then place securing bolts along the narrow edge of the sail to hold the two sides of the fold together. Each wing is $107\,\mathrm{cm}$ tall and $20\,\mathrm{cm}$ long ($214\,\mathrm{cm}^2$ area), a photo of these can be seen in figure 3. This design created a very balanced sailing configuration and gave the potential to use the sails to trim steering or to replace the steering should the rudder fail. We conducted several tests of this boat without any control system running and found that it was able to hold a course providing the sails had been set correctly. It was able to "goose swing" (setting the sails to opposite tacks) when sailing down wind. This greatly enhanced downwind stability compared to AROO's single sail configuration. We also tested "heaving too" (where the sails and rudder are configured to counteract each other and keep the boat in one place) as a method of station holding but the boat was dragged sideways by wind and currents, in part due to its small shallow keel. The inherent stability of this configuration offers great hope for one of the key requirements of a sailing robot, a boat which requires virtually no actuator use to maintain itself on a present course, thus keeping power consumption to an absolute minimum. As with AROO we found that the sails were actually too big and although they sailed fine in 30 knots of wind, anything more and the boat would have healed excessively. To remove the problem of cables running through the mast, the wind sensor was moved from the sail to its own mast near the stern where it was less likely to experience any turbulence caused by the sails. The wing sails were controlled by two stepper motors taken from an old printer, these worked acceptably well in light winds and laboratory tests but in stronger winds the gears driving the sails would slip and the sails would drift from their original position. Our original control algorithm kept track of sail position by keeping a record of the distance moved since the sail was last calibrated, however when the sail began slipping this strategy failed. We later added a potentiometer to keep track of sail position to counter this problem.

Fig. 3. Arc's Dual Wing Sails.

C. BeagleB's wingsail

BeagleB [4] was developed commercially by Robosoft [1] for Aberystwyth University and took on much of the knowledge gained in the previous two boats. BeagleB is $3.5\,\mathrm{m}$ long and its hull is based on sailing dinghy intended for disabled sailors, this design is particularly stable and designed to self right very quickly should it capsize. BeagleB is propelled by a $2.55\,\mathrm{m}^2$ ($3\,\mathrm{m}$ x $85\,\mathrm{cm}$) carbon fibre wing sail (shown in figure 5), this is only 60 percent of the sail usually used on this hull. However this is probably still too large for sailing under extreme conditions. Construction of the wing required significant effort and took several weeks to complete, it represented over $25\mathrm{percent}$ of the cost of entire boat. Although experience with ARC had shown that a dual sail configuration was highly stable, BeagleB's hull was not suitable for two wings and the resulting design actually proved to be sufficiently stable. The sail is limited to only 130 degrees of rotation by stays on either side, to the best of our knowledge it is the only example of a sailing robot with a stayed wing sail. Wind sensing is provided by a commercial ultrasonic wind sensor (a Furuno Rowind) on top of the sail. This is mounted on an aluminium tube which runs down the centre of the sail and does not rotate, this removes the need to take sail position into account when determining the wind direction. As shown in figure 4 the sail is moved by an LA12 linear actuator mounted on the deck below the sail, the end of the actuator arm consists of a toothed plastic rack. The base of the sail contains a circular pinion which is driven by the actuator. Beagle's wing sail has proven to be highly stable, capable of sailing in winds as light as 1 knot however it has only been tested in winds of approximately 20 knots, mainly due to the danger to humans in deploying such a large boat under strong winds.

[1] www.robosoft.fr

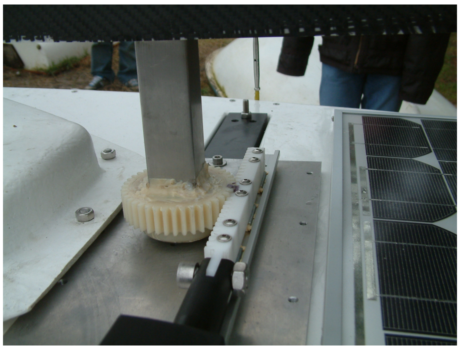

Fig. 4. Beagle B's Rack and Pinion connector for the wing sail.

D. MOOP's wingsail

The latest boats produced by Aberystwyth University are known as the MOOPs (Miniature Ocean Observation Platform). They are an attempt to build a set of small, cheap, simple, mass produceable and lightweight but highly robust robots capable of crossing the Atlantic but also intended for shorter term missions to research control system strategies, a photograph of the first prototype can see in figure 6. Their hulls are only $72\,\mathrm{cm}$ long and the total weight is only around 4kg. Such a small hull has been selected to reduce cost and the difficulties in handling the boat, especially when launching and recovering. We had found that with Beagle-B at least two people were required to rig and launch the boat and that in busy waters a sufficiently fast chase boat was always required. With the MOOPs we wanted to develop a boat which could easily be handled by one person and that could be transported in a normal car or checked in as baggage on a flight. The small size also reduces the probability of causing damage to another boat in the event of a collision. The low cost and relatively simple construction process now allow us to produce a new boat in under three weeks and we hope to deploy a small fleet of them during summer 2009. Each boat features a

Fig. 5. Beagle B and its wing sail.

single wing sail $52.5\,\mathrm{cm}$ x $13\,\mathrm{cm}$ ($68\,\mathrm{cm}^2$) constructed from a polystyrene and glass fibre composite, these are intended to be small enough to remain sailing in strong winds. A carbon fibre rod run's through the centre of the sail to reinforce it and to run cabling through to the wind sensor. To allow the sail to be removed, a 5 pin PS/2 keyboard DIN plug is placed approximately 1/3 of the way along the inside of the tube. The sails also float (adding extra stability in the event of capsize) and are built to keep all the internal wind sensor electronics dry. In addition to being small, light and floating these sails were incredibly cheap compared with Beagle-B's carbon fibre sail, however it is unlikely that we could scale this design up to a $2.5\,\mathrm{m}^2$ sail. The sails were relatively simple to construct, wing shape is cut from a large polystyrene block using an electrical cutter (which is simply a wire which heats up from the electricity running through it) and using a cardboard outline as a guide. The centre of this must then be hollowed out and the carbon fibre rod inserted, the wind sensor must be mounted on the top. The wing is then wrapped in fibre glass cloth which is attached with epoxy. The entire process takes at least one day to complete (not including construction of the wind sensor).

Although previous experience with ARC demonstrated that dual sail configurations are preferable, the small size of the hull makes it difficult to place two sails. We have considered attempting to place two sails upon the hull and possibly a slightly increasing the hull length of future boats. Variants of the wing have been developed with both rotary and ultrasonic wind sensors. The sail is positioned by a heavy duty servo and can rotate a maximum of 210 degrees. Although over the long term a servo is likely to wear out and if used incorrectly can easily burn out they are exceptionally simple to program, cheap, fast and repeatable within a few degrees. So far (during relatively short and "gentle" tests) they have performed exceptionally well. From casual observations this wing sail appears to be able to sail at least 45 degrees to the wind and is very stable close hauled or reaching. However their stability down wind, especially under gusty conditions is poor and frequent jibes are experienced. This is suffered by all wing sails (and arguably many other sail designs) and is not a problem unique to the MOOPs but because of their small size only minimal force is required to induce a jibe. One possible solution to this is to tack down wind, never allowing the stern of the boat within at least 25 degrees of the wind.

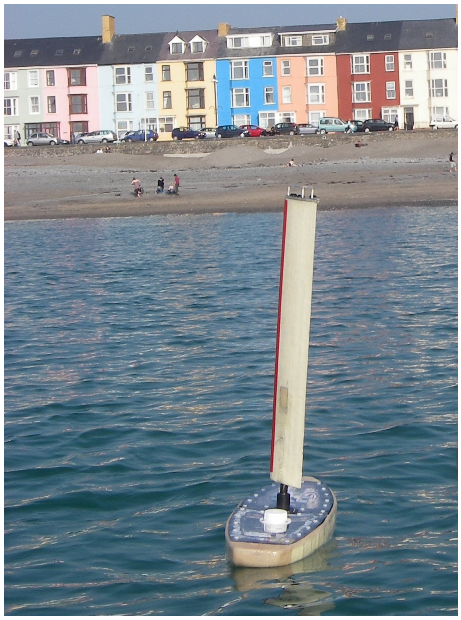

Fig. 6. The first MOOP sailing off Aberystwyth.

E. Conclusions on Wing Sail Design

Although each boat presented here differs in size, shape and its intended design goal we have observed a number of useful attributes for a wing sail. The sails should be waterproof and buoyant so that they can survive being submerged and so that they will aid in righting the boat in the event of capsize. They should also be lightweight to simplify storage, transportation and rigging. If possible cables should not be run through the sail, if they are then either the rotation of the sail must be limited or cables should run through a tube which does not rotate. Finally the size of the wing sail needs to be kept small, although when designing boats for racing there is the temptation to increase sail size to increase speed this is often counterproductive when sailing in winds over 30 knots when such boats find themselves leaning beyond 45 degrees most of the time. Given that there is currently an absence of suitably reliable and simple reefing mechanisms for wing sails, any boat which wishes to continue sailing in strong winds must be equipped with a very small sail.

III. Wind sensing

Wind direction sensing is a key requirement for a sailing robot in order to allow it to set its sail position and course correctly. Wind speed information is less important but may still be useful to know whether it is futile to attempt to sail the boat either due to there being too much or too little wind.

In order to deploy sailing robots unassisted for long periods of time the ideal wind sensor must be robust enough to withstand strong winds, salt corrosion and the buildup of salt deposits and waterproof enough to sustain occasional submergence and prolonged periods of rain and spray.

There are essentially three classes of wind sensor, pure mechanical sensors which use a potentiometer to measure wind direction, contactless mechanical sensors which use magnets and hall effect sensors to sense direction inside a waterproof enclosure or ultrasonic sensors which detect the movement of air inside them. Mechanical sensors can suffer from wear and tear and can be difficult to waterproof. Ultrasonic sensors offer the obvious benefit of being totally free of moving parts but are typically more expensive and can experience problems when water droplets collect on the sensor. Contactless mechanical systems in many ways offer the best of both worlds as they are relatively simple to manufacturer and operate but far easier to waterproof than traditional mechanical systems, however they are likely to suffer from some level of mechanical wear over prolonged periods.

A. Mechanical

The traditional approach to wind sensing has been to simply attach a wind vane to a continuous rotation potentiometer. Such an approach is taken by many off the shelf commercial products and offers a cheap and simple method for sensing wind direction. Using a simple analogue potentiometer allows for a typical resolution of 8 or 10 bits depending on the analogue to digital converter being used. Typical accuracy is within a few degrees, dependant upon the exact design of the vane. As the only component is essentially a resistor of a $\mathrm{few\,kohms}$, power consumption is very low. However they suffer from a number of major drawbacks:

- They can suffer from mechanical wear and tear reducing their effectiveness over time.
- They are difficult to waterproof as the shaft of the potentiometer must somehow connect with the vane.
- If the boat lists to one side and the vane may be affected by gravity.
- They perform poorly in light winds when the wind is too weak to keep them in position.
- Most potentiometers have small dead band where they cannot accurately measure the position.

Simple mechanical sensors were used on the first two boats built at Aberystwyth - AROO [3] and ARC [5] and have since been employed on some variants of the MOOP boats, a photograph of one of these sensors on a MOOP wing sail can be seen in figure 7.

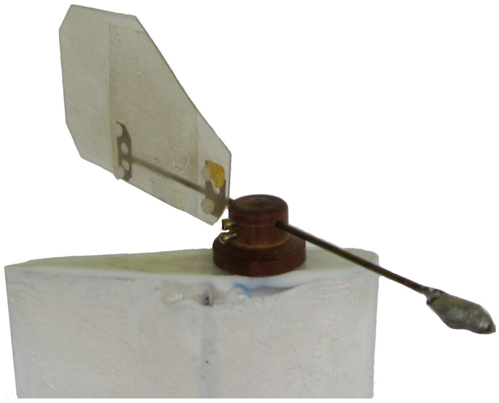

Fig. 7. The Mechanical Wind Sensor used on AROO, ARC and MOOP.

B. Contactless Mechanical

A contactless mechanical system has been developed by the University of Porto for the FASt project [6]. This solution is based upon contactless magnetic rotary encoders using the family of integrated circuits available from AustriaMicroSystems (AS50xx)[2]. These small devices integrate in a single chip a set of Hall effect sensors with analogue and digital interfacing circuitry and provide an absolute angle measurement by computing the absolute orientation of the magnetic field created by an appropriate magnet placed at a close distance of the device case. Main features of these devices include resolution from 8 to 12-bit, a maximum integral non linearity of ± 1.4, digital output through a serial interface, sampling rate above $2.5\,\mathrm{kHz}$ and power consumption below $20\,\mathrm{mA}$ (some chips even provide low power modes with consumption below $2\,\mathrm{mA}$).

Reading the absolute position of a mechanical wind vane can be done by simply attaching a small magnet ($6\,\mathrm{mm}$ diameter, $0.55\,\mathrm{grams}$) in the axis of the wind vane, and place one of these rotary encoders close to the magnet and conveniently aligned with the rotational axis. To protect the device from moisture and water the whole electronics can be embedded in some isolating material like Epoxy or liquid rubber. Figure 8 shows a possible arrangement for this device.

The arrangement shown in figure 8 was assembled in a prototype wind vane for a robotic sailboat. The sensor uses the integrated circuit AS5040 (10 bit resolution), providing an accuracy of ± 1 degree. The chip was mounted in a small printed circuit board and the electronic board was moulded with Epoxy resin (figure 9-a). The small magnet was attached to the shaft with an aluminium case and a small ball bearing holds the rotating part of the assembly (figure 9-b). Both parts are fixed together with screws that allow the mechanical alignment of the sensor with respect to the magnet axis

[2]http://www.austriamicrosystems.com

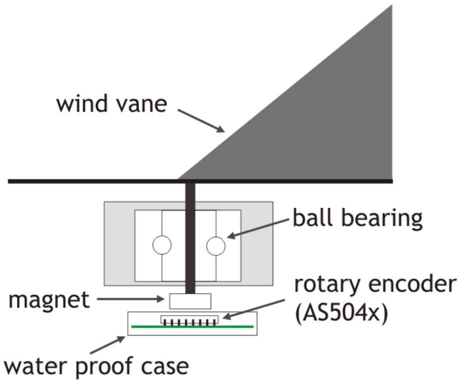

Fig. 8. A schematic of a mechanical wind vane read by a contactless magnetic rotary encoder.

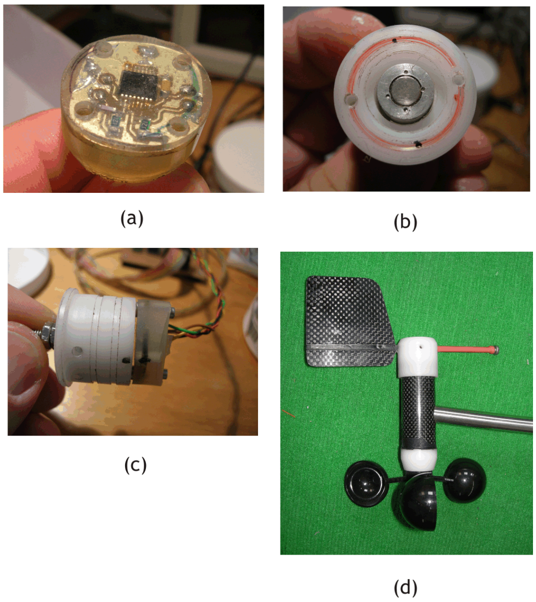

Fig. 9. The magnetic sensor embedded in Epoxy resin (a), the magnet attached to the vane axis (b), the assembly of the two parts (c) and the final wind sensor (d).

(figure 9-b). The whole set was then housed in a carbon fibre tube, that also supports the anemometer at the other end (figure 9-d). The anemometer is a conventional 3 cup rotor with another magnet that activates a Hall effect switch in each revolution.

1) Reading the wind sensor: The interface with the AS5040 is done with a synchronous serial interface that reads the 10-bit digital word representing the absolute position of the magnet, plus a few additional status bits used to validate the data read. This interface is implemented as a custom digital controller on a FPGA device that hosts the whole digital system of the autonomous sailboat, sampling the sensor at a 50 Hz rate. To filter the readings, a low-pass mean filter was also implemented in digital logic, using a 64-tab sliding window. Because of the discontinuity from 359 to 0, the computation of the angle average cannot be done as a simple arithmetic mean. This module implements an averaging process that, for each new sample, computes the arithmetic mean of all the deviations from the current averaged wind direction and then adds it to the previous average. The output averaged value is made available to the central processor as a 9 bit two's complement integer in the range $[-180, +180]$. Figure 10 shows a block diagram of the module that performs this operation.

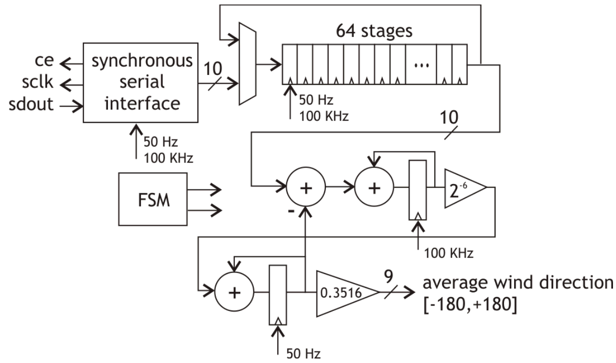

Fig. 10. The wind direction average calculator.

C. Ultrasonic Sensors

Ultrasonic sensors offer the promise of a sensor which is free of moving parts allowing them to operate over prolonged periods without suffering from mechanical wear. The theory of operation is relatively simple, a transmitter transmits a burst of ultrasonic sound and this is picked up by a receiver. The strength and direction of the wind will affect the amount of time the signal takes to reach the receiver. A measurement of this is taken by measuring the time of flight or phase difference between the transmitter and receiver. By using two receivers (although depending on configuration only one transmitter maybe required) placed 90 degrees apart two axis information can be derived. By taking the arc tangent of the times from each receiver the angle of the wind can be determined. Wind speed can be determined by taking their sum.

Although several commercial off the shelf sensors are available they cost several hundred pounds/dollars/euros and are not particularly small as they were designed for yachts not sub 4 metre sailing robots! We chose to try and build a simple and low cost sensor for the MOOPs using a water proof ultrasonic transmitter and two receivers as well as two NAND gates, comparators and capacitors. Instead of measuring the time of flight directly (which is highly processor intensive) we measure the phase difference between the signal we transmit and the one we receive. The rate of movement of air through the sensor is measured by timing the flight of a 40kHz ultrasound signal reflected off the top plate from the transmitter to the receiver. The received signal is amplified by a comparator and NAND'ed with the original 40khz signal (which was generated by the PWM channel on a PIC microcontroller) and used to charge a capacitor. The voltage at which the capacitor stabilises depends on the degree of overlap between transmitted and received pulses. Changes in air speed through the sensor cause changes in the degree of overlap. A block diagram of this process is shown in figure 12 and a photograph of the transmitter and receiver arrangement is shown in figure 11. Whilst this scheme is very simple, the results vary depending (as are all devices based on the speed of sound in air) on the density of the air in the sensor. The chief cause for variation in density is variation in the ambient air temperature which requires compensation. At the time of writing our prototypes do not have this compensation, thus they require recalibration before each use to compensate for changes in the ambient temperature. Calibration is performed automatically on start up, and is thus not too onerous, but work is on-going to incorporate temperature compensation into the sensor and processing software. We have been able to reduce the level of noise in the sensor by moving some of the electronics from inside the hull to the top of the mast. This reduces the level of attenuation in the signal by cutting the length of the cable between the receiver and the comparator. Development of the electronics and software for the sensor will require significant further effort to achieve a standard suitable for long term missions, but the advantages offered seem to be worthwhile: no moving parts, a total weight of around 50g, a total cost of less than £30 (sterling) and very low power consumption.

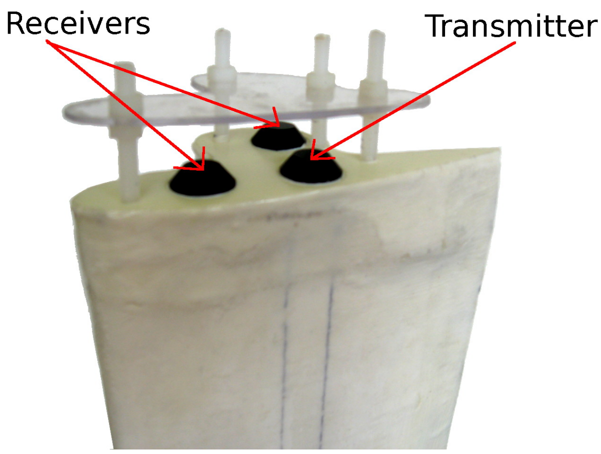

Fig. 11. MOOP's Ultrasonic Wind Sensor.

We conducted a series of laboratory tests using a small desk fan. Figure 13 shows the raw wind direction as recorded while the sensor was spun 360 degrees. An averaging algorithm (described in section III-D) was used to generate a line of best for the data. Prolonged testing suggests the accuracy is relatively poor at somewhere between 10 and 20 degrees, however we have found this is sufficient to position sail appropriately as we only use a total of 10 unique sail positions. Unfortunately despite this promising laboratory test real world operation was less successful due to the problems with temperature compensation. We have also found that if large droplets of water appeared on the sensor that the properties of the signal were severely distorted although it was possible to detect this

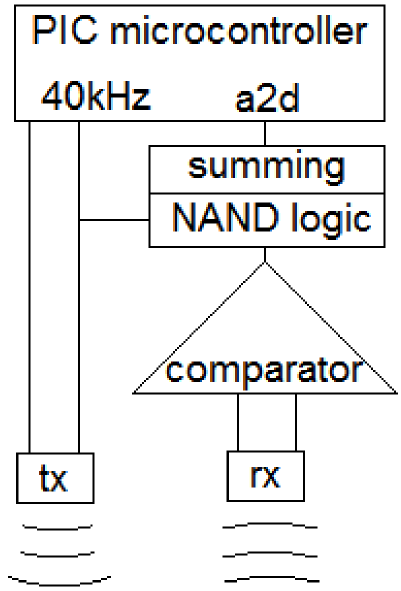

Fig. 12. A block diagram of the ultrasonic wind sensor.

as the sensor would return an extremely large raw value. Smaller droplets or a thin film of water on the sensor did not appear to be a major problem.

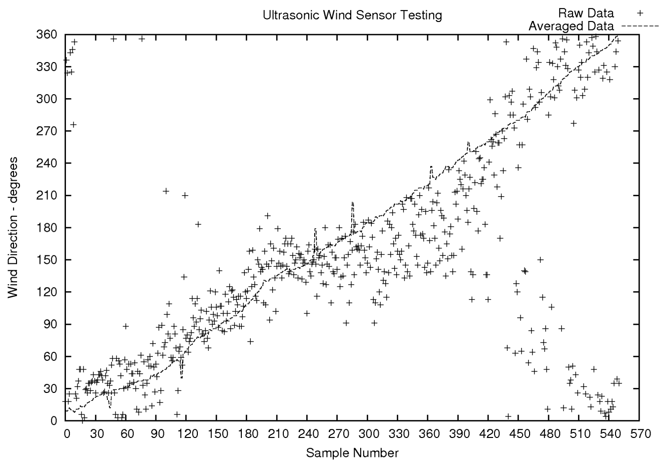

Fig. 13. Raw data from the ultrasonic sensor show against averaged data. This with the sensor initially pointing into the wind. The sensor was then gradually spun over 360 degrees.

D. Algorithms for Long Term Averaging of Wind Direction

Even the best wind sensors are likely to experience some level of noise and wind typically varies by a few degrees even under optimal conditions. For this reason it seems sensible to attempt to average the wind sensor readings over time. One possible approach is to store a large number of readings in a sliding window and constantly take an average (as described in section III-B1), however as we increase the amount of time we wish to average over the size of this buffer increases.

Depending on the target computer architecture memory maybe extremely limited. The sliding window approach also gives equal weighting to all readings, regardless of age. If readings are taken over a few seconds or even minutes this is unlikely to be a problem, but if readings are taken over hours then we would probably need to reduce the importance of older readings. If we do not then changes in wind direction risk being preserved in the average reading and the values will not be sufficiently reliable.

Instead of the sliding window approach, we can take a constant running average. In order to take an effective average we must introduce a significant amount of historical data but we also wish to introduce a bias towards newer data as the wind may have genuinely shifted and we would like our control system to be able respond. Any system dealing with rotational data is likely to encounter a problem when averaging data which lies either side of the wrap around point, for example averaging 350 degrees and 5 degrees. Our solution to this problem is to take an average of the sine and cosine components of the angle and then recombine them by taking their arc tangent. The algorithm is defined as follows:

$$
\begin{aligned}
s &= s + (sin(w) - s)/r \\
c &= c + (cos(w) - c)/r \\
d &= atan2(s, c)
\end{aligned}
$$

Where s is the average sine of the wind, c is the average cosine, w is the current wind direction and d is the calculated wind direction, r is the rate of change. The larger the value of r the slower the average will change.

In all our robot designs the wind is measured relative to the boat direction of the boat. In order to produce a long term average we must use the true wind direction (the compass heading of the wind) so we must subtract the current compass heading from the wind direction. As it takes sometime for the average heading to update we bootstrap the averages with the first reading we take in the hope that this is approximately correct and will result in a faster convergence upon the real wind direction.

This algorithm has been shown to work well, but in conditions where the wind is constantly shifting (such as on mountain lakes where the wind funnels around nearby terrain) it can be too slow to update. In cases such as these taking an instantaneous or near instantaneous reading seems more sensible. Therefore it might be more appropriate to use the sliding window method described in section III-B1 or to set the value of r very low.

IV. Conclusions and Future Work

We have demonstrated the feasibility of wing sails to drive sailing robots and their potential to be highly robust but also discovered their limitations with regards to reefing and downwind sailing. Further work needs to be undertaken to optimise wing shapes and sizes and to test the full potential of using multiple wing sails to improve performance and stability.

We have shown that a waterproof ultrasonic wind sensor can be constructed using simple electronics and at a low cost, but that temperature calibration and long term averaging are essential. We have also shown that a contactless mechanical sensor is also a viable option for long term use. For sailing robots operating for short periods of time in sheltered conditions a basic mechanical sensor provides a cheap and viable option but is not suitable for long term usage.

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